# Phase-locking on the beat signal of a two-mode 2.7 terahertz metal-metal quantum cascade laser

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## Abstract:

*We have studied the linewidth and phase-locking of a 2.7 THz quantum cascade laser by using a superconducting bolometer mixer. The 8 GHz beat signal is compared with a microwave reference with a feedback to the laser bias current. Phase locking has been demonstrated, resulting in an extremely narrow beat linewidth of less than 10 Hz. Under frequency-stabilization conditions we find that the line profile is virtually Lorentzian with a long-term minimum linewidth of the THz modes of about 6.3 kHz. Temperature dependent measurements suggest that this linewidth does not approach the Schawlow-Townes limit.*

Significant progress in the development has made quantum cascade lasers[1] (QCLs) promising coherent solid-state THz sources for various applications. As demonstrated, a THz QCL can be applied as local oscillator (LO) for heterodyne receivers operating at several THz frequencies,[2,3] which are crucial for astronomical and atmospherical high-resolution spectroscopic sensing. For those applications a narrow emission linewidth of a QCL under frequency stabilization or phase locking is essential. In the case of a heterodyne space interferometer,[4] phase locking to an external reference is absolutely required. Here we report the first demonstration of phase locking of the beat signal of a two lateral-mode THz QCL to a microwave reference. Under frequency stabilization conditions, we are able to study the emission spectrum of a THz QCL in a systematic way, which previously was impossible. We use a QCL-device based on the resonant phonon design.[8] The active region contains 176 GaAs/$Al_{0.15}Ga_{0.85}As$ quantum-well modules, with a total thickness of 10 μm. The cavity of the QCL is a double-sided metal-semiconductor-metal waveguide, which is 40 μm-wide and 1 mm-long. When operated in a CW mode at a cold plate temperature of below 15 K, the emission spectrum measured by a Fourier-transform spectrometer (FTS) shows two closely spaced lines at 2.742 THz and 2.749 THz, respectively. They correspond to two different lateral lasing modes with unequal intensities. Their intensities and frequencies depend on the bias current of the QCL and the cold plate temperature. Furthermore, the effective indexes of refraction corresponding to the two modes are different and should also have a different temperature or current dependence. The maximum lasing output power per facet is roughly 1 mW.

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To obtain the beat signal of the QCL, we use a spiral antenna coupled NbN hot electron bolometer (HEB) mixer, which can be operated up to at least 3-4 THz. The HEB is similar to those described in Ref. 9 and has a comparable sensitivity.

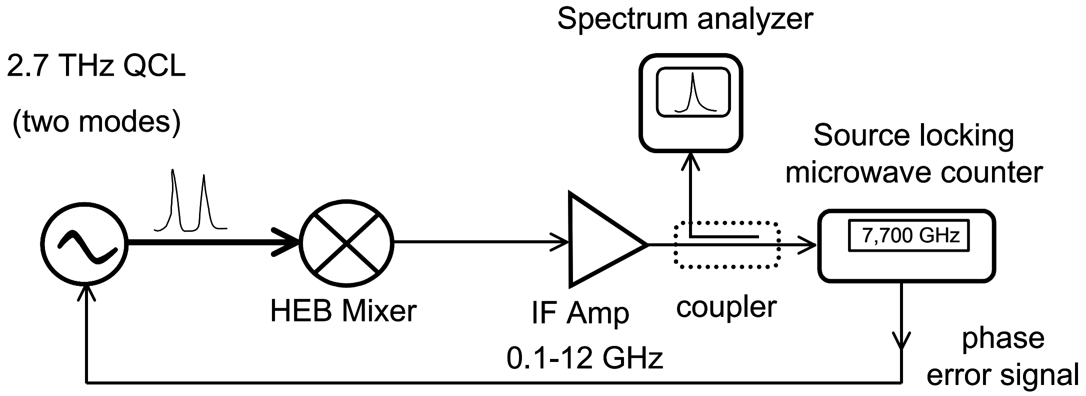

FIG.1. Schematic diagram of the experimental setup to phase lock of a two-mode THz QCL.

Figure 1 shows a schematic diagram of our measurement setup. The output beam of the QCL is focused onto the quasi-optically coupled HEB mixer. The IF (beat) output is fed into an EIP 575 source-locking microwave counter. The phase error correction signal of this counter is fed back into the bias-current circuit of the QCL using a variable resistor. We create a phase lock condition by using the PLL with a high loop gain with a maximum regulation bandwidth of 10 kHz. Figure 2 shows a typical set of power spectra of the beat signal recorded by the spectrum analyzer using a fixed video bandwidth (VBW), but different resolution bandwidths (RBW). Apart from the phase error correction signal from the EIP 575, both the temperature of the cold plate and the DC bias current are fixed. The spectra in figure 2 are actually power spectra of the phase difference between QCL beat and reference signal. As indicated in the figure, the linewidth seems to be reduced with reducing the RBW of the spectrum analyzer. Apparently the linewidth is too small, e.g. smaller than 10 Hz, to be measurable due to the limited RBW of 10 Hz. The data demonstrate that for an offset from the center frequency less than the PLL regulation bandwidth most of the signal power is located in a central peak of (near-) zero bandwidth. *This is a clear indication of phase locking.* The spectra are reproducible and stable for an arbitrary-long time. Experimentally, we can show that the QCL behaves as a current controlled oscillator, which is the key to enable phase locking. As shown in the inset of figure 2, the beat frequency decreases monotonically with increasing bias current for a given cold plate temperature, e.g., from 7.9 to 7.5 GHz with the rate of roughly 10 MHz/mA. This means that phase locking conditions can be realized for all bias points, and moreover that stabilization of the beat frequency implies stabilization of the THz frequencies of both laser modes. The second part of our studies involves the study of the free running laser line profile and linewidth. Starting from phase locking conditions we now reduce the loop gain such that the central frequency of the beat signal remains the same but the line shape is no longer influenced by the phase locking. Under this frequency-stabilization, we are able to measure the power spectrum of the beat signal of the QCL in a systematic way, e.g. as a function of the cold plate temperature or the bias current. Figure 3 shows a measured beat signal with the minimum linewidth observed in this experiment, fitted with a Lorentzian curve. We draw attention to several interesting features. The fit shows the spectrum to be predominantly Lorentzian, as expected if the noise is due to spontaneous emission. In some other cases, we find that a Voigt function gives a better fit than the Lorentzian, suggesting the coexistence of other noise sources, e.g. 1/f noise and noise interference pick up.

The minimum (FWHM) linewidth is found to be 12.6 kHz. Knowing that this beat signal results from a convolution of two similar lines and assuming that their profiles are virtually Lorentzian, the lower limit of the linewidth of *an individual emission line* should be 6.3 kHz. Note that this is the narrowest linewidth ever reported in THz QCLs and is actually a few orders of magnitude smaller than required for astronomical and atmospheric observations. The linewidth of a THz QCL should be limited by quantum noise through spontaneous emission and is expected to be described by the Schawlow-Townes limit .

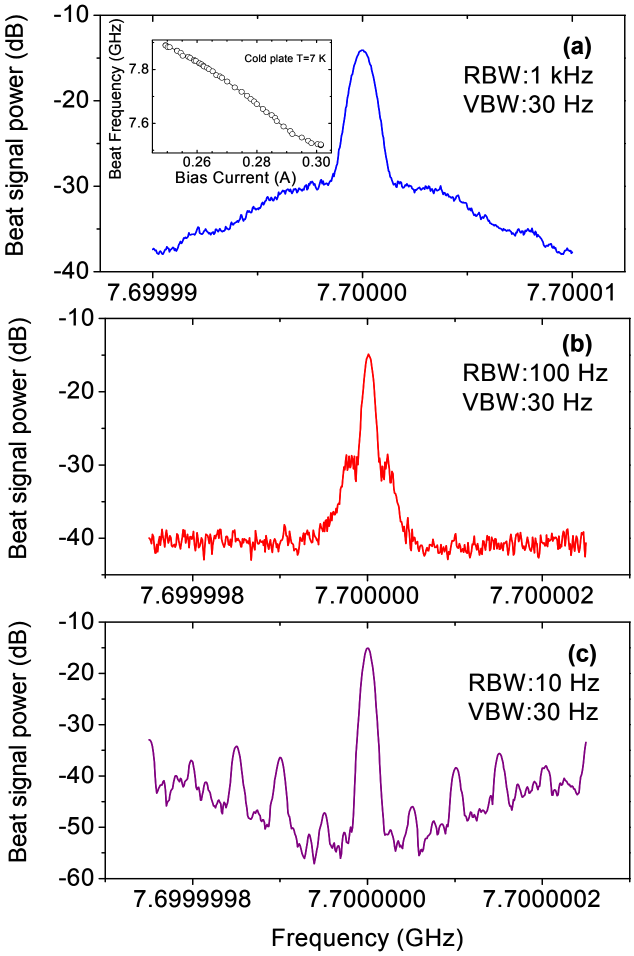

FIG. 2 The power spectra of the beat signal of two lateral-mode THz QCL that is phase locked to a microwave reference around 7.7 GHz recorded with different resolution bandwidths (RBW), but a fixed video bandwidth (VBW) in the spectrum analyser. Other lines appeared in (c) are due to the pick-up of 50 Hz signals. The inset in (a) shows the beat frequency as a function of bias-current of the QCL at cold plate temperature of 7K.

$$\Delta\nu_{ST} = (\frac{N_2}{N_2 - N_1})\frac{(2\pi h\nu)(\Delta\nu_c)^2}{P}$$

(1)

Here $N_{1,2}$ are the populations in the upper and lower laser states; $\Delta\nu_c$ is the cold cavity waveguide and mirror losses ($\alpha = \alpha_w + \alpha_m$ ); $P$ is the internal power in the mode relating linewidth and equals $\alpha v_g/2\pi$ with the group velocity $v_g$ and the total loss $\alpha$ of the to $P_{out}$ by $P_{out} = (\alpha_m / \alpha)P$ . We assume eq. 1 to be valid for each of the two emission lines. Using the following inputs: $N_2/(N_2-N_1)=1.3$, $\alpha_w \sim 10$ cm$^{-1}$ at 2.7 THz, $\alpha_m = 2.2$ cm$^{-1}$, and $P_{out} \sim 1$ mW, we derive a Schawlow-Townes linewidth $\Delta\nu_{ST} = 0.7$ KHz, which seems to be 10 times smaller than the measured linewidth. In view of large uncertainties in these input parameters, the result is not conclusive yet. Nevertheless, this represents a first serious attempt to investigate the ultimate linewidth of a THz QCL.

Eq. 1 suggests that the linewidth should be inversely proportional to the laser power. To test this, we have studied the linewidth of the beat signal as a function of cold plate temperature. The results are shown in figure 4.

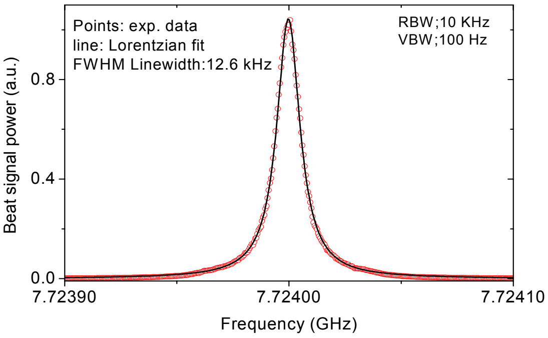

FIG. 3 Measured power spectrum of the beat signal under frequency stabilization (data points)[11]. The curve is a fit with a Lorentzian profile.

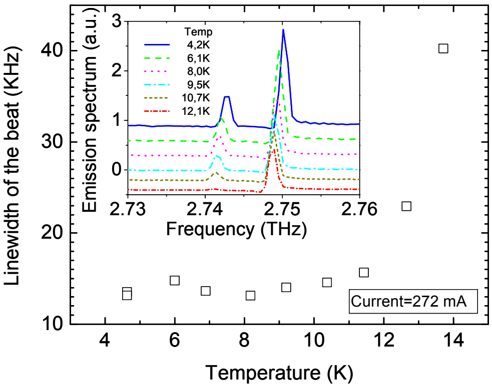

FIG. 4 Linewidth of the beat signal as a function of the cold plate temperature of the QCL. The inset shows emission spectra of the two-mode QCL taken at several temperatures. For clarity an offset in the intensity for each spectrum is introduced.

We notice that, despite that the intensity (considered to be equivalent to the power) of both emission lines decreases monotonically (see the inset of figure 4), the linewidth remains virtually independent of temperature up to 12 K. Clearly the linewidth does not follow Eq. 1 and consequently does not approach the quantum-noise limit.

In summary, we have succeeded in achieving phase stabilization of a 2.7 THz QCL through the beat signal of its two lateral-modes, demonstrating the feasibility of phase-lock of the THz signal itself. Under frequency-stabilization conditions we have been able to study the lineshape and linewidth of the free running QCL in a controllable manner and found the narrowest linewidth of 6.3 kHz.

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